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MEMORANDUM FOR PR (In-House Publication)

FROM: PROI (TI) (STINFO)

01 December 1999

SUBJECT: Authorization for Release of Technical Information, Control Number: **AFRL-PR-ED-TP-1999-0231**
Liu, C.T., "Fracture Mechanics of Solid Propellants" (EF)

49th JANNAF Propulsion Meeting (Tucson, AZ, 14-16 Dec 1999)

(Statement A)



Fracture Mechanics of Solid Propellants

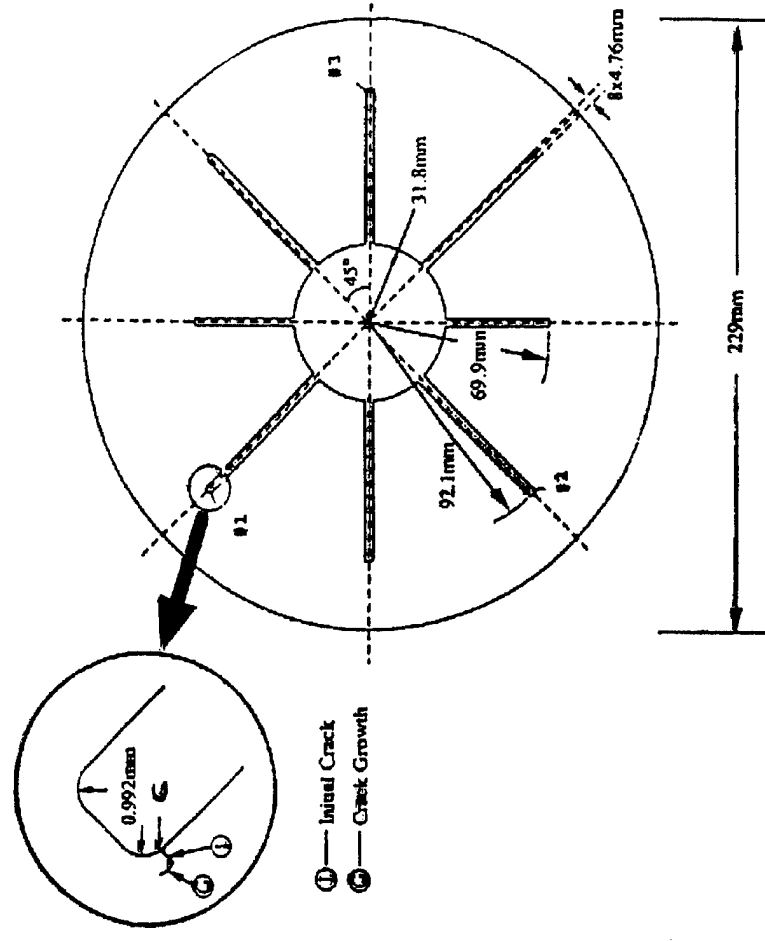
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Introduction

- What is the Initial Crack Length at the High Stress Location?
- Does the Crack Propagate Under Service Loads?
- If the Crack Propagates, How Does it Propagate?





Fracture Mechanics of Solid Propellant

• Goal:

- Develop Advanced Structural Design and Service Life Prediction Technologies.

• Objectives:

- Gain an Improvement in Understanding of Damage Mechanisms and Fracture Behavior in Solid Propellants and Insulator/Liner/Propellant Bond Systems.
- Develop Methods to Predict Crack Growth .

• Payoffs:

- Increase Structural Reliability of Solid Rocket Motors.
- Reduce Motors Replacement Costs.



Fracture Mechanics of Solid Propellant

•Funding Profile (\$K)

Material Mechanics Research (AFOSR)

FY 98	FY 99	FY00	FY01	FY02
300	200	188	188	188

Minuteman Support (Minuteman SPO Hill AFB)

FY 98	FY 99	FY00	FY01	FY02
220	220	220	220	220



Fracture Mechanics of Solid Propellants

State of the Art

- Deterministic Approach
- Material is Homogeneous
- Crack Growth Models are Assumed to be Independent of the Initial Crack Length

New Technology from Program

- Provide Reliable Crack Growth Models
 - * Account for Inhomogeneity of Microstructure
 - * Account for Initial Crack Length Effect
- Provide Guidance for Formulating High Crack Growth Resistance Solid propellants
- Make Defect-Tolerance Analysis Methodology Feasible



Technical Challenge and Approach

• Technical Challenge:

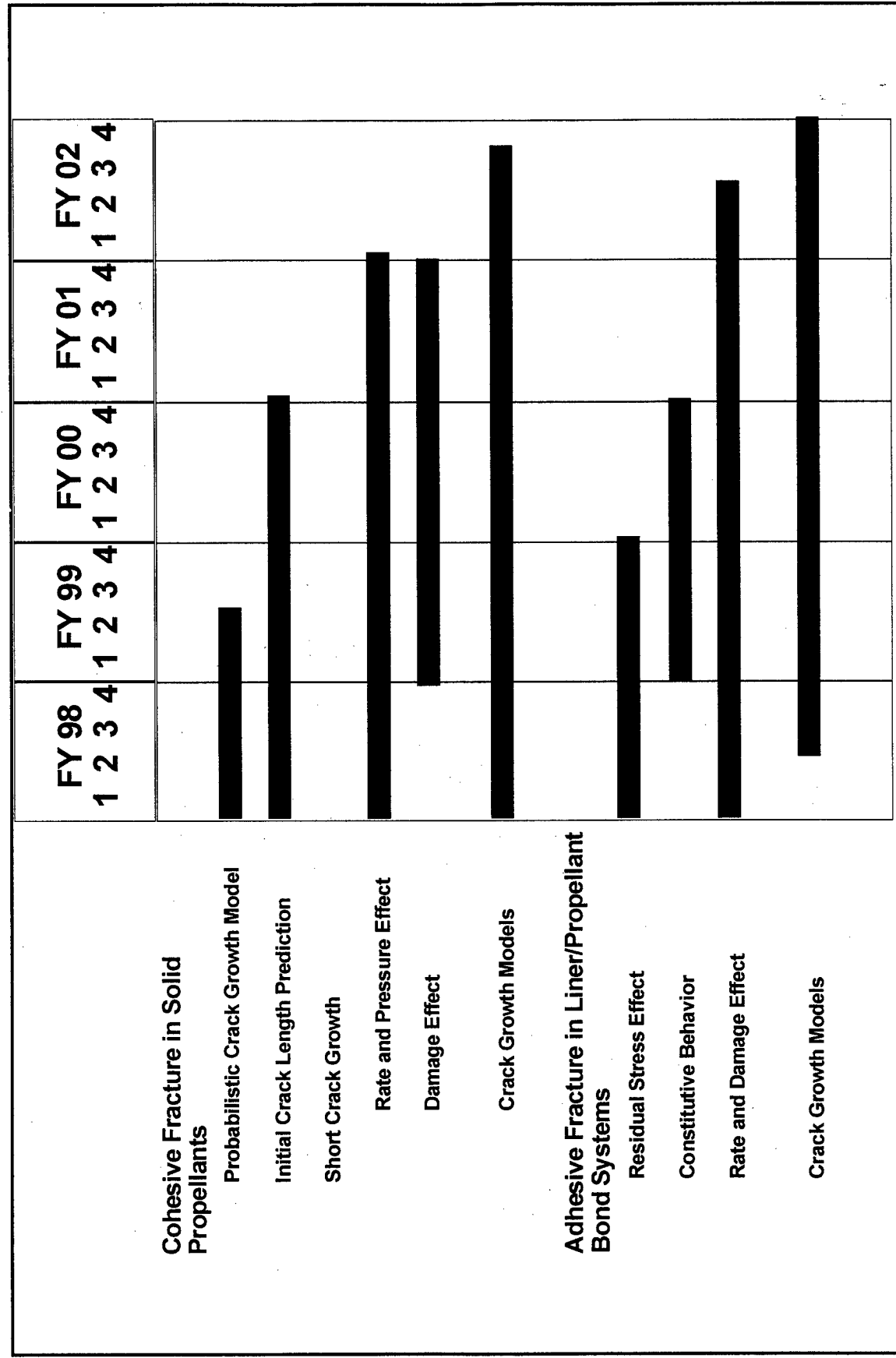
- Large and Time-Dependent Deformation
- Short Crack and Stress Raiser Interaction
- Multi-layer Structures with Time-Dependent Material Properties and Property Gradients

• Approaches:

- Non-Linear Viscoelasticity
- Non-Linear Fracture Mechanics
- Experimental Mechanics
- Damage Mechanics
- Fracture Mechanics
- Experimental Mechanics
- Non-Destructive Testing and Evaluation
- Fracture Mechanics
- Experimental Mechanics
- Numerical Modeling

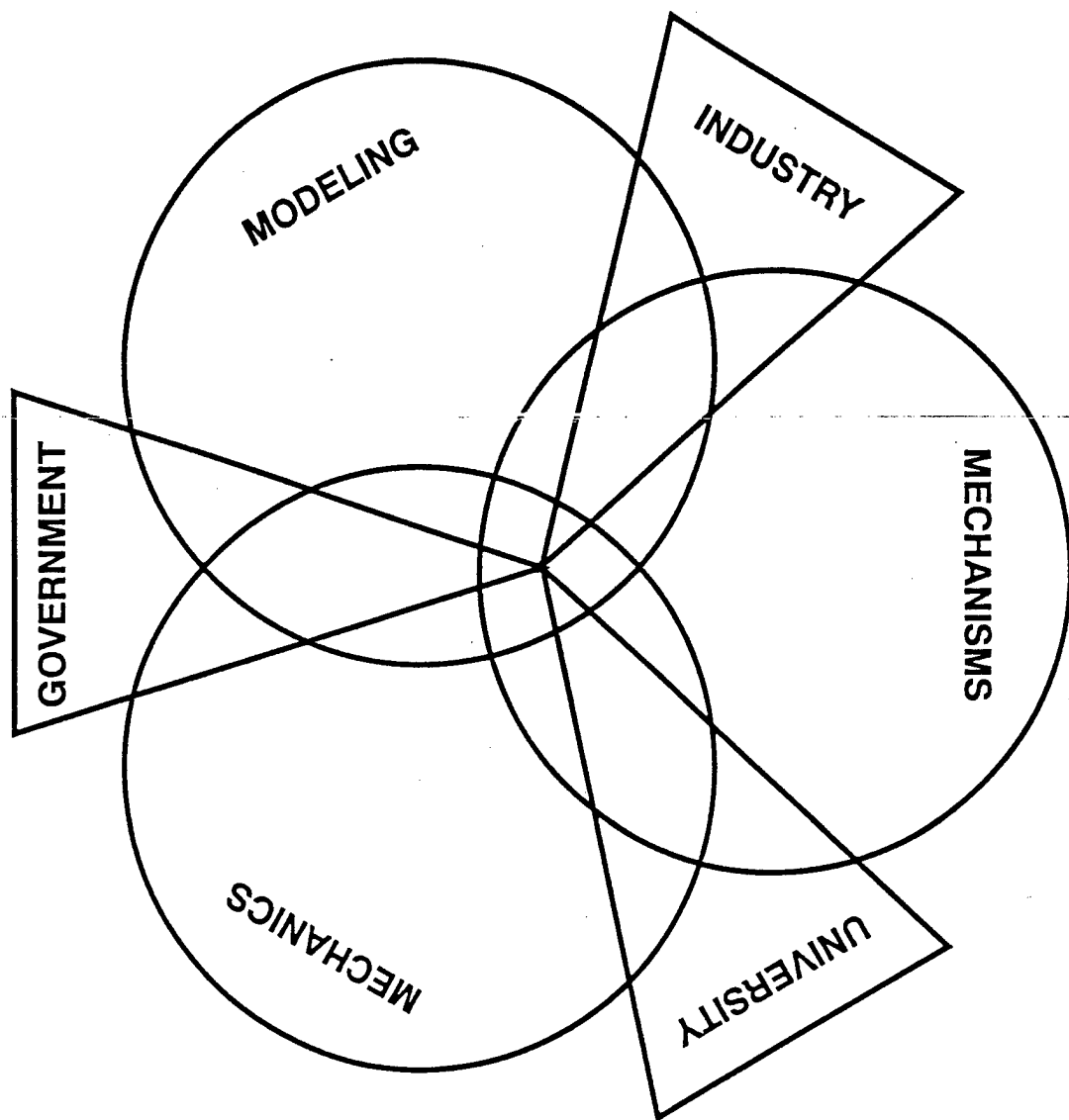


Milestone Chart



Approach....

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Past Year's Accomplishments (Material Mechanics Research)

1. Developed a rate-dependent probabilistic crack growth model.
2. Developed a mechanistic criterion to predict the initial crack length in a high stress region
3. Proved that, for $a_0 \leq 0.1$ in., Linear Fracture Mechanics cannot be used to determine the critical stress intensity factor for the onset of crack growth
4. Proved that for short cracks ($a_0 \leq 0.1$ in.) and long cracks ($a_0 \geq 0.2$ in.), the crack growth behavior is similar
5. Proved that nonhomogeneous microstructure has no significant effect on the path-independent nature of the J-integral
6. Incorporated a time-dependent nonlinear viscoelastic model in a finite element computer code
7. Determined the stress distribution along the front of a part-through surface crack in the bond system

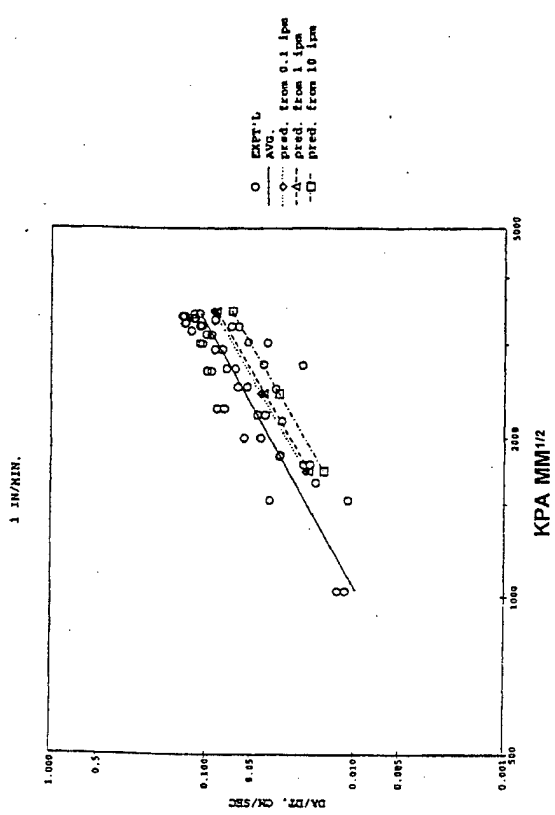
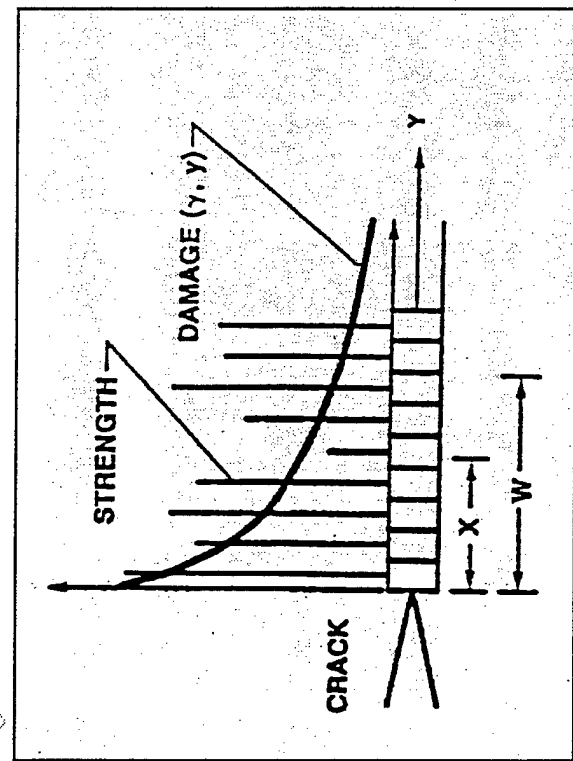


Past Year's Accomplishments (Minuteman Support)

- **Determined the Representative Area of MM 1st Stage Propellant.**
- **Determined the Fracture Toughness for the onset of Crack Growth Under 1000 psi Pressure.**
- **Conducted X-Ray Tests and Analyzed the Test Data.**
- **Conducted Photoelastic Tests to Determine the Effect of Specimen Geometry on the Stress Fields at Interfacial Crack Tip.**
- **Conducted Finite Element Analysis to Determine the Effects of Specimen Geometry, Material Property, and Crack Length and Location on the Stress Intensity Factor at the Crack Tip.**



The Rate-Dependent Crack Growth Model can be Used to Predict Crack Growth at Different Strain Rates with Good Accuracy



$$E[a] = K_1^{2(1+\gamma)} (b_1 \gamma / \beta \gamma)^{\gamma} (1+\gamma) (1-\gamma)^{-\alpha \gamma} \gamma^{-1} [1 - (1+\alpha \gamma) e^{-\alpha \gamma}] \Gamma(1-\gamma) C^{1+\gamma}$$

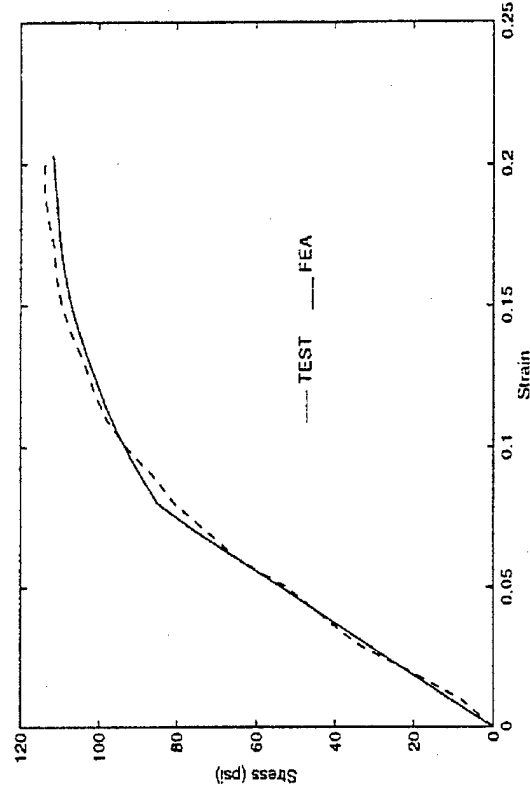
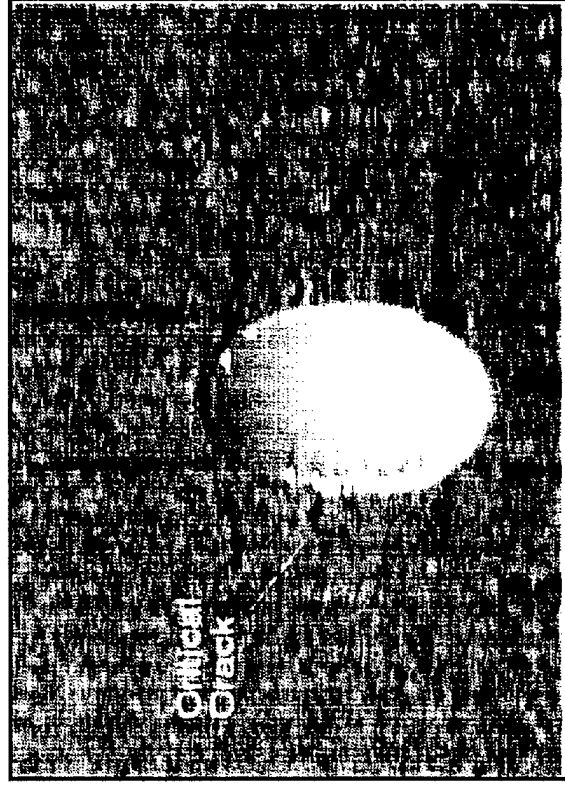
$$\gamma = 1/\alpha, \quad C = (\pi/8) [1/\beta \Gamma(1-\gamma)]$$

- The parameters β and b are proportional to strain rate whereas α and g are insensitive to the strain rate
- The probabilistic crack growth model can guide propellant formation to increase resistance to crack growth of solid propellant



Good Correlation Exists Between the Predicted and the Measured Crack Initiation Load and the Initial Crack Length

- Based on a Micro-Macromechanical Model and a Stress Instability Criterion, the Predicted and Measured Average Initial Crack Lengths are 1.2 mm and 1.0 mm for $D=0.25$ inch Hole and 1.5 mm and 1.3 mm for $D=0.5$ inch Hole.

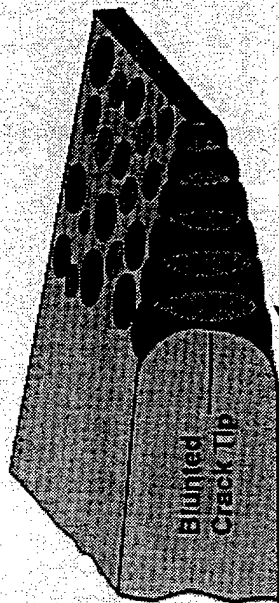
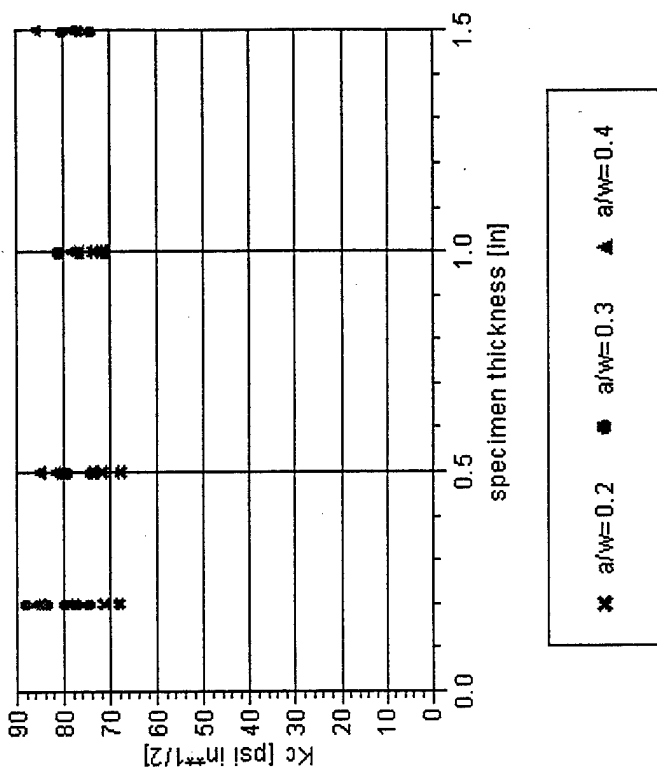


Stress-Strain Curve at Strain Rate 0.02/min



For the Solid Propellants Studied, Plane Strain Fracture Toughness Does Not Exist

- Experimental Findings Reveal that Severe Damage Develops at the Crack Tip, Fracture Toughness is Independent of Specimen Thickness, and the Crack Front is Straight.
- Three-Dimensional Micro-Macro Damage Analyses Reveal that Damage Distribution is Uniform along the Crack Front.
- Three-Dimensional Linear Elastic Numerical Analyses Reveal that Crack Tip Damage Induces a Uniform Distribution of Mode I Stress Intensity K_I Through the Specimen Thickness, Resulting in a Straight Crack Front.

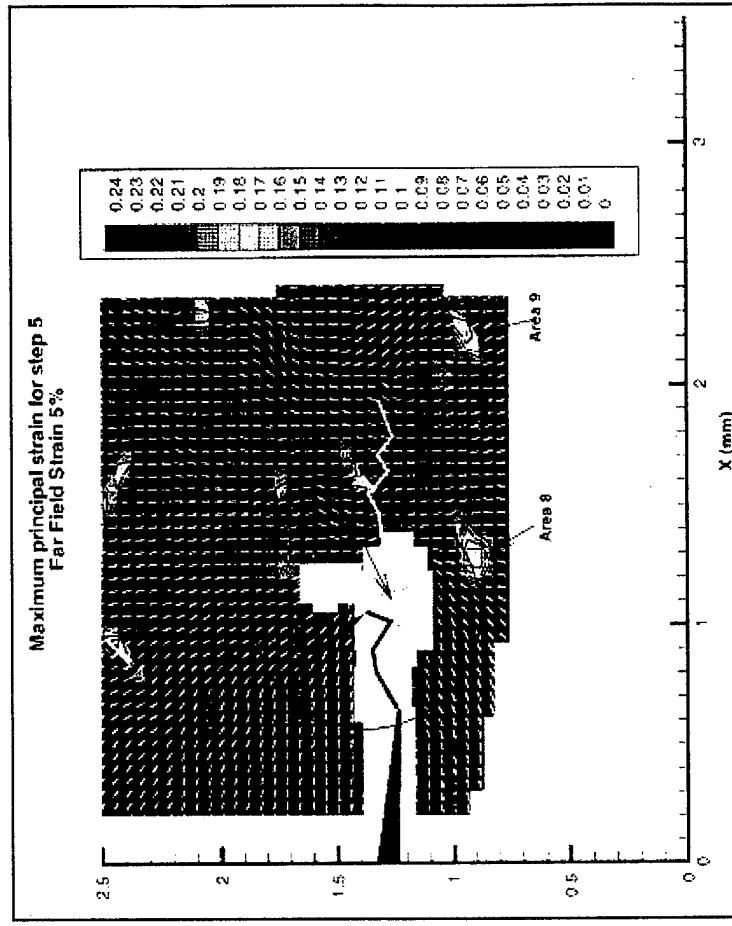
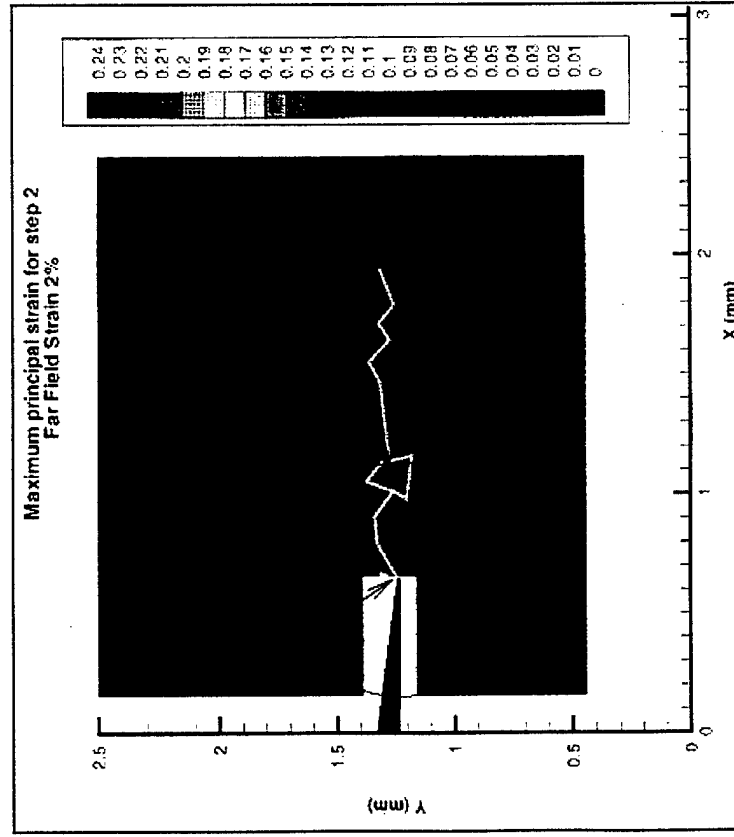


Highly Damaged Zone

Crack Tip Damage Model



Microstructure Induces a Large Inhomogeneous Variation in the Strain Field Near the Crack Tip

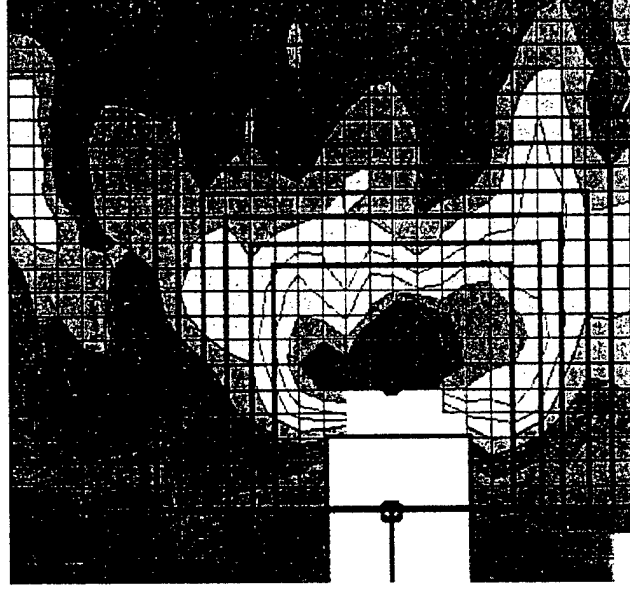
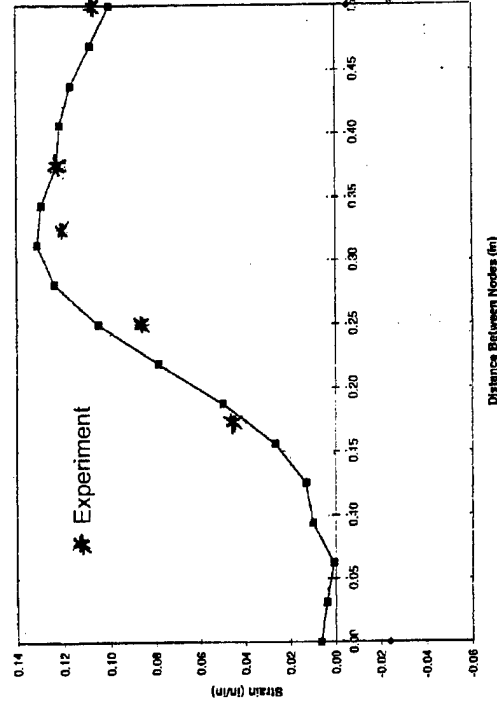


* The Interaction Between Large Deformation and Crack Propagation Process Localizes around The Crack Tip Regions



Microstructure has no Significant Effect on the Path-Independent Nature of the J-Integral

E_{yy}



- A Good Correlation Exists Between Experimentally Measured and Numerically Calculated E_{yy} Along a Given Path of Integration
- The Mean and the Coefficient of Variation of the J-Integral Along Seven Paths are 633 Pa m and 0.03, Respectively



Conclusions

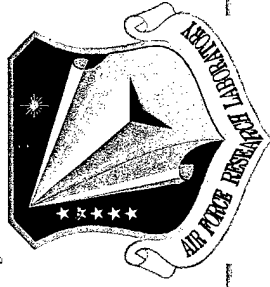
- The heterogeneity of the microstructure plays a key role for local damage and strain distributions near the crack tip.
- The high strain field is localized within 1 mm of the crack tip.
- Specimen thickness has no significant effect on the fracture toughness for the onset of crack growth.
- The developed technique can be used to predict the initial crack length with good accuracy.
- On the macroscopic scale solid propellants can be considered a homogeneous continuum.
- The developed probabilistic crack growth model can be used to predict crack growth under different strain rates with good accuracy.

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Current Activities (Material Mechanics Research)

- **Pressure Effect on Short and Long Cracks Growth.**
 - Different Pressure levels and strain rates
- **Viscoelastic Modeling of Crack Growth.**
 - Including Local Strain Rate Effect
- **Pre-Damage Effect on Short Crack Growth**
 - Numerical Modeling
 - Nondestructive Testing and Evaluation
- **Propellant/Liner/Propellant Bond System Fracture Characterization.**



Current Activities (Minuteman Support)

- **Determine the Relationship Between NDE Parameters and Material Properties.**
- **Determine the Fracture Toughness of MM 1st Stage Solid Propellant at 200 in/min Displacement Rate (56 min⁻¹ Strain Rate) Under 1000 psi Pressure.**
- **Conduct Photoelastic Test to Determine the Stress Field at Star Tip of MM1st Stage Grain.**
- **Conduct Finite Element Analysis to Determine the Stress Intensity Factor as a Function of the Crack Length.**
- **Fabricate Propellant / Liner / Propellant Bond Specimen and Conduct Material Characterization Tests.**



Future Activities (FY01)

(Material Mechanics Research)

- **Pre-Damage Effect on Short Crack Growth.**
- **Numerical Modeling of Crack-Defect Interaction.**
- **Pre-Damage Effect on Fracture of Propellant/Liner/Propellant Bond System.**
- **Fracture Characterization of Insulator/Liner/Propellant Bond System.**



Future Activities (FY01)

(Minuteman Support)

- **Determine the Relationship between NDE Parameters and Material Properties.**
- **Develop Crack Growth Models Including Pressure and Strain Rate Effects.**
- **Develop a Statistical Crack Growth Model Based on Small Number test Data.**
- **Determine the Rate Effect on Interfacial Fracture Toughness and Crack Growth of a Propellant/Liner/Propellant Bonded Specimen.**